APPLICATIONS OF PHASE COMPARISON
IN DIRECTION FINDER SYSTEMS

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IN DIRECTION FINDER SYSTEMS

by

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INTRODUCTION

Radio direction finding has its origin almost as early as radio communications itself, but with the advent and development of radar and loran, the use of direction finders took on a secondary importance. However, as is usually the case, development was not stopped or abandoned. Much effort has been, and is being, spent in research and improvement of direction finding systems, and, logically enough, from this concerted effort many new uses for direction finders evolved.

As its name implies, it is an aircraft instrument of great value and importance. Small privately-owned vessels which cannot afford radar and/or loran are usually equipped with a direction finder. Locating enemy transmissions, monitoring and administrative control of aircraft flights, homing, and rescue operations are more recent uses to which direction finding has been adapted and found very suitable.

Direction finders are classed in many ways, for example according to the type of antenna system which they use to receive the signal. These may include multi-turn loop antennas, spaced vertical antennas, ADCOCK or U antennas, or balanced coupled antennas. Classification may also be made as to whether the direction finder makes use of a rotating or of a nonrotating antenna. Usually portable types as used in aircraft and shipboard installations use rotating antennas; whereas shore based systems use fixed antenna systems.

Regardless of the antenna array, however, each direction finder

system falls into one of two categories. Each measures the direction of an incoming electromagnetic wave by a voltage comparison. Voltages which are derived from the signal whose direction is desired are compared to a reference voltage, the phase or amplitude of which can be controlled. Either these voltages are compared as to amplitude or as to phase. There are many systems in use for each of these comparison methods and it is the purpose of this paper to discuss a few of these systems which use the method of phase comparison. Several systems will be described. A rotating loop antenna system, systems using vertical antennas, and the most recent use of direction finders called omnirange will be covered. All of the material presented in this paper is drawn from periodicals, pamphlets, and publications. Superscript numbers refer to numbered references in the bibliography.

CHAPTER ONE

ROTATING LOOP SYSTEMS

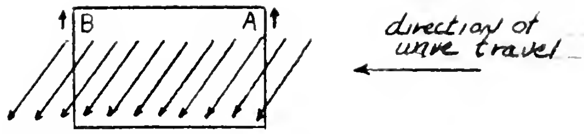
The great majority of present day direction finders make use of a rotating antenna of the multi-turn loop type. It has the merit of simplicity, can be made weatherproof and rugged, and, if the loop possesses a sufficiently high 'Q', will produce a good signal while being very compact. The output voltage of a loop antenna varies directly as the number of turns, the area of the loop, and the cosine of the angle of the incoming wave with respect to the direction parallel to the loop. It varies inversely as the wave length. Since the output varies directly with the cosine of an angle, the loop possesses a 'figure of eight' reception pattern, provided the dimensions of the loop are small as compared to a wavelength.

Since two minima are obtained with a simple loop antenna, it is quite impossible to decide which is correct. Modern direction finder systems are usually equipped with a means of determining absolute direction or 'sense'. The receiving properties of the vertical loop and a vertical antenna that is non-directional in the horizontal plane are combined. The non-directional antenna has a circular reception pattern. When the loop and the vertical antenna voltages are equal and added in phase, a 'cardioid' pattern is obtained, giving a single minimum with a maximum 180 degrees away from the minimum. Hence, the ambiguity as to the actual direction of the incoming signal no longer exists. Accordingly, the non-directional antenna used with the loop is called a

'sense antenna'. Furthermore, the minimum of the cardioid is in the plane of the loop and 90 degrees away from the minimum of the 'cosine' diagram of the loop alone.

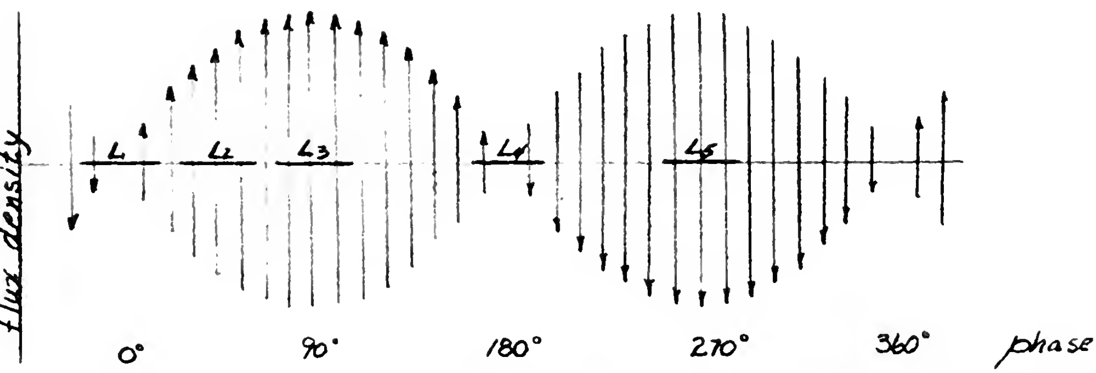
The radio frequency carrier in the loop channel reverses when the loop is rotated through a null point. This can be seen by reference to figures 1-3. When the horizontal lines of flux in the incident wave cut the two vertical members of the loop, the instantaneous voltages induced in members A and B are in the same direction. Corresponding currents then flow in opposite directions around the loop (see figure 1) and will completely neutralize one another if the instantaneous voltages induced in members A and B are the same. Since the magnetic field of the wave is alternating, the instantaneous flux density at any point along the line of wave travel varies sinusoidally.

When the phase of the wave at the loop is 0°, (see figure 2a) as at loop position L_1, the lines of flux cutting the loop are in opposite directions at its two vertical members. Therefore the induced voltages in the vertical members are in opposite directions. The resulting currents are then in the same direction around the loop, and the loop voltage is maximum. At the 180° phase point (loop position L_4) the loop voltage is again maximum but in the opposite direction around the loop. At the 90° and 270° phase points (loop positions L_3, L_5), the flux density and direction is the same at both sides of the loop so that the resultant loop voltage is zero. At all other phase points the flux density is different at the two sides of the loop although the flux direction is the

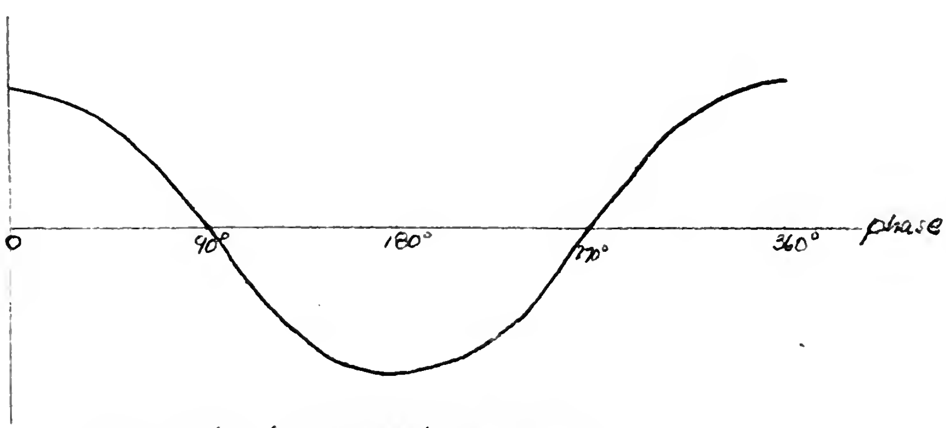


opposing currents induced in loop antenna

FIGURE 1.



a) top view of loop at various phases of the incident wave

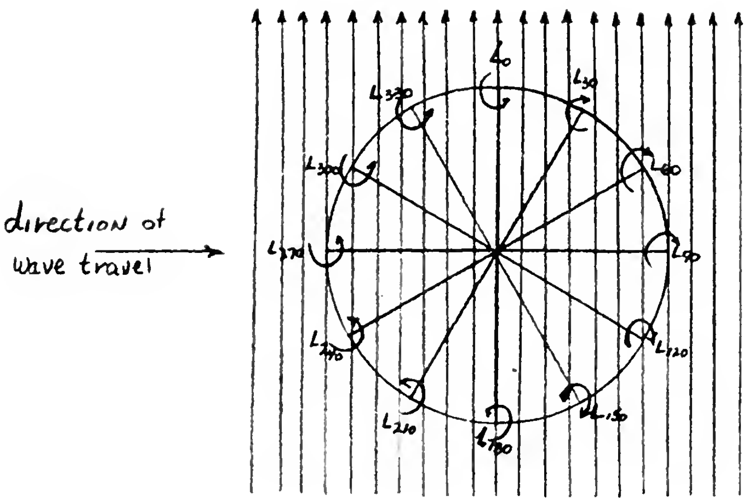


b) one cycle of induced loop voltage.

FIGURE 2.

same. The effective loop current is then the difference of the two opposing currents induced in the two sides, and the loop voltage is proportional to the current differences. From figure 2b it can be seen that the effective loop voltage differs in phase from the incident wave by 90°.

When the loop is in position L_{0° (see figure 3) its plane is parallel to the lines of flux and perpendicular to the direction of wave travel so there is no flux linkage and hence zero or null response. As the loop is turned to successive positions as shown (position L_{30°, L_{60°, etc.) it will link successively more and more lines of flux until, at position L_{90°, its plane is parallel to the direction of wave travel and it links the maximum flux. As the loop is rotated further it links less and less flux until, at position L_{180° the flux linkage is again zero and its response is again a null. The flux linkage and loop response increases with continued clockwise rotation, reaching a maximum in the L_{270° position, in which the loop is again parallel to the direction of wave travel. The response decreases over the remainder of the rotation back to the original null. It is seen that for the first half of the loop rotation from the original null to the second null position, the flux linkage relative to the loop is always in the same direction, whereas for the remainder of the rotation from the second null position back to the first, the flux linkage relative to the loop is in the opposite direction (see curved arrows of figure 3). The phase of the loop voltage for the two halves of the rotation will then differ by 180°, the phase reversal occurring as the loop is turned through its null position.



Variation in flux linkage due to loop rotation about a vertical axis

FIGURE 3.

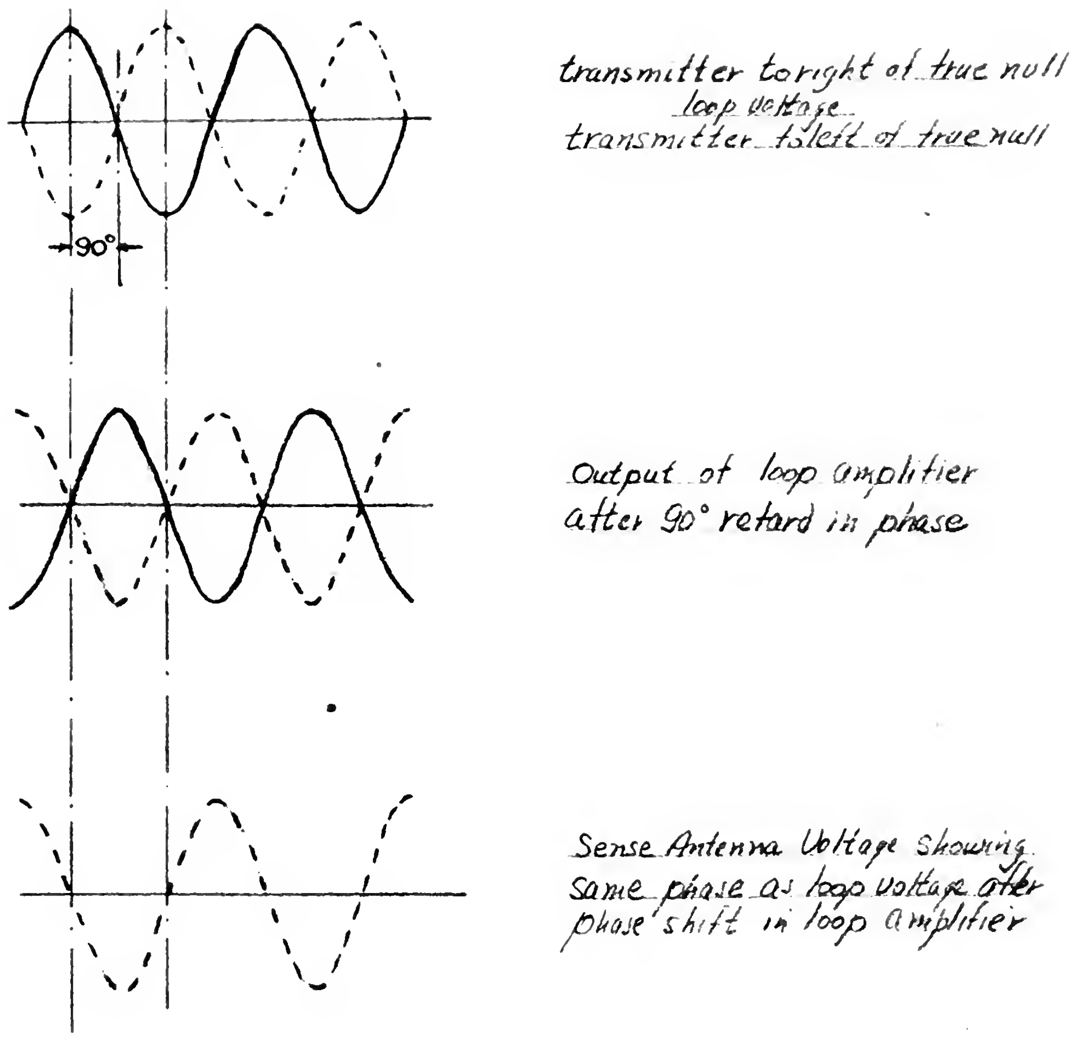
A typical system [1,2] using a loop antenna and sense antenna combination operates as follows. The radio frequency signal picked up by the loop is amplified and then passed through a phase shifting network which gives the signal a 90 degree phase lag. This makes the loop signal either in phase or 180 degrees out of phase with the sense antenna voltage, the phase being dependent upon transmitter direction being right or left of a null (see figure 4.). From the phase shift network the loop signal is coupled in phase to the grids of a two element balanced modulator. Simultaneously, these grids are fed in push-pull at an audio frequency; for example, 115 cycles from the a.c. vibrator supply. Thus in the balanced modulator stage the radio frequency voltage is modulated at 115 cycles in a radio frequency 'phase' determined by which edge of the loop is nearer the transmitter (see figure 5.). The output of the balanced modulator is a carrier-suppressed double sideband signal, the sidebands corresponding to the 115 cycle modulating frequency. The modulated loop signal and the sense antenna signal are simultaneously coupled to the grid of a common amplifier and thence to a typical receiver consisting of a converter, intermediate frequency amplifiers, and second detector (see figure 6.). The output of the second detector consists of a 115cps voltage which is either in phase or out of phase with respect to the original 115cps voltage. The phase of the audio frequency voltage at the detector of the receiver is also changed by 180 degrees when the loop is reversed (see figure 7.).

The reversing of the audio frequency phase causes the loop to be driven by a reversible motor to a point of null loop signal pickup. Since the motion may be in one direction when the initial position of the [illegible] system [illegible] ing a loop antenna [illegible]

operate as follows. The radio frequency signal [illegible] loop is amplified [illegible] through a phase shifting network which gives the signal [illegible]. This makes the loop signal either in phase or 180 degrees out of phase with [illegible] voltage, the phase being [illegible] direction [illegible] null (see figure [illegible]). [illegible] shift network [illegible] loop signal is [illegible] in phase [illegible]. [illegible], these [illegible] 115 cycles [illegible] supply. Thus in the [illegible] stage [illegible] frequency voltage is modulated at 115 cycles in a ratio frequency [illegible] which edge of the loop is nearer the transmitter (see figure [illegible]). The output [illegible] balanced modulator is a carrier-suppressed [illegible] sidebands [illegible], the [illegible] corresponding to the 115 cycle modulating frequency. The modulated loop signal and the [illegible] antenna signal are simultaneously coupled to the grid of a common [illegible] a typical receiver consisting of a converter, [illegible] frequency amplifiers, and [illegible] detector (see figure [illegible]). [illegible] voltage which [illegible] compared to the original [illegible]. The phase of the [illegible] frequency voltage [illegible] the detector [illegible] loop is reversed (see figure 7).

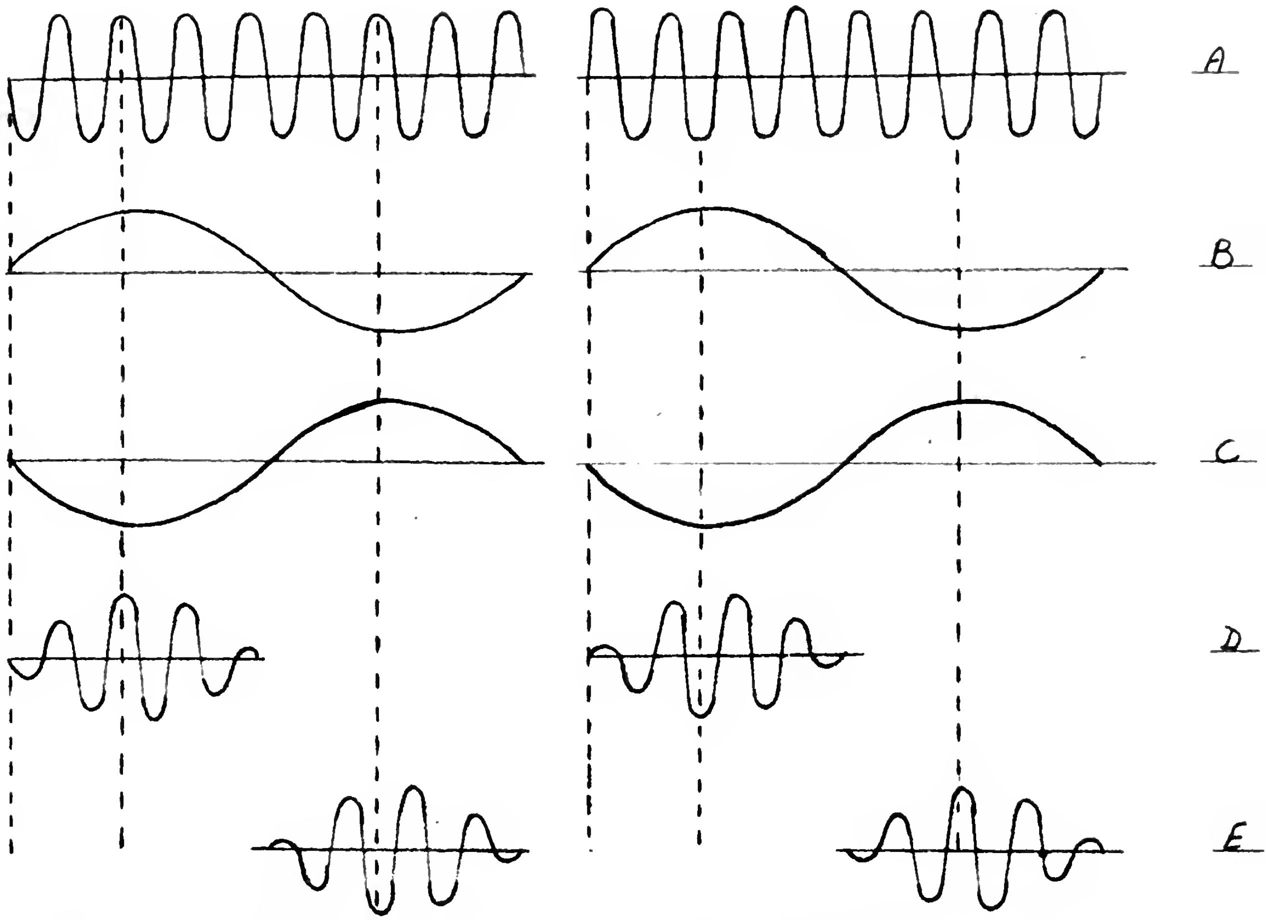
The reversing [illegible] frequency [illegible] to be driven by a reversible [illegible] motor [illegible].

[illegible]



loop and sense antenna voltages

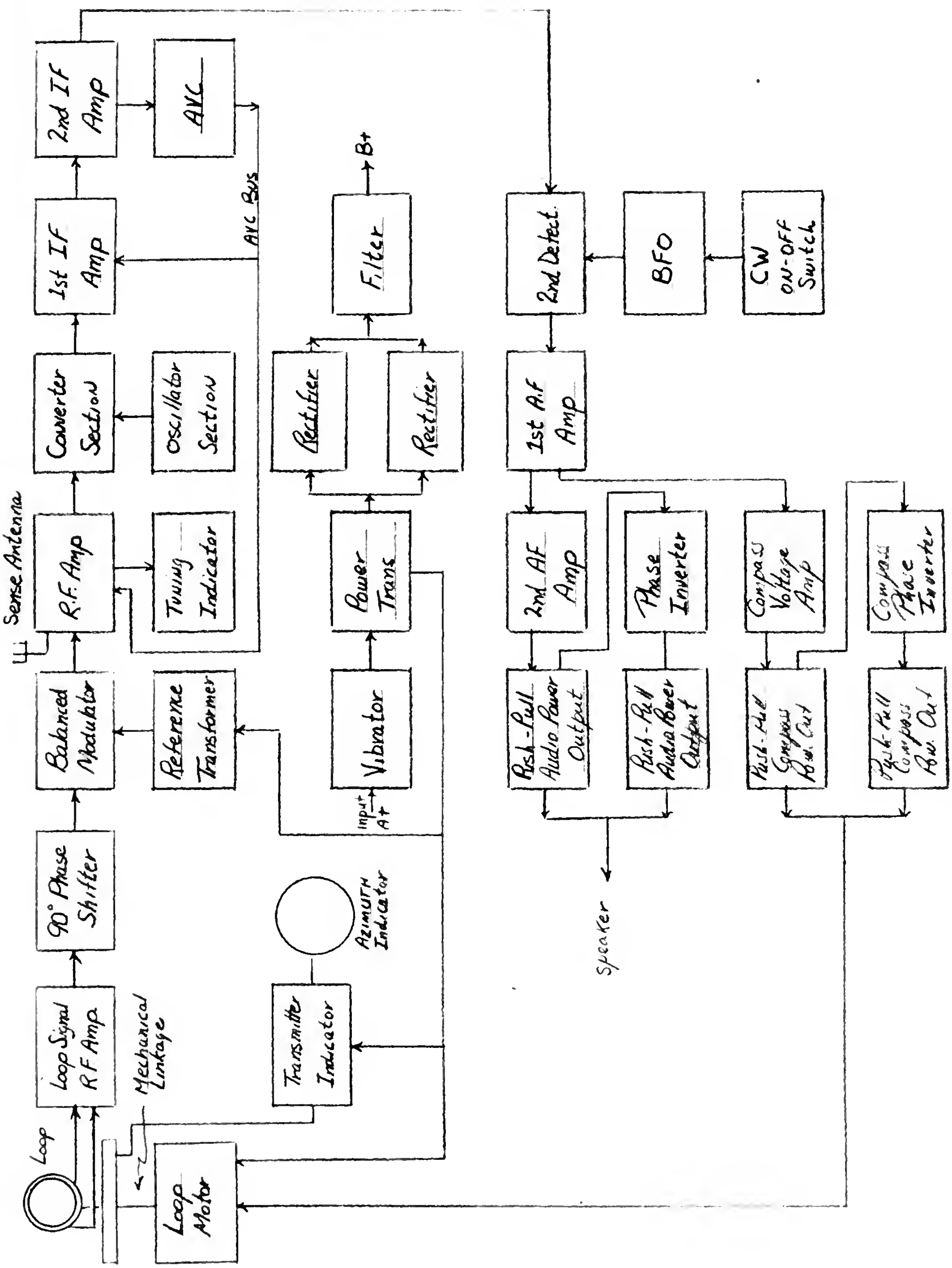
FIGURE 4.



Transmitter to left of true null — transmitter to right of true null

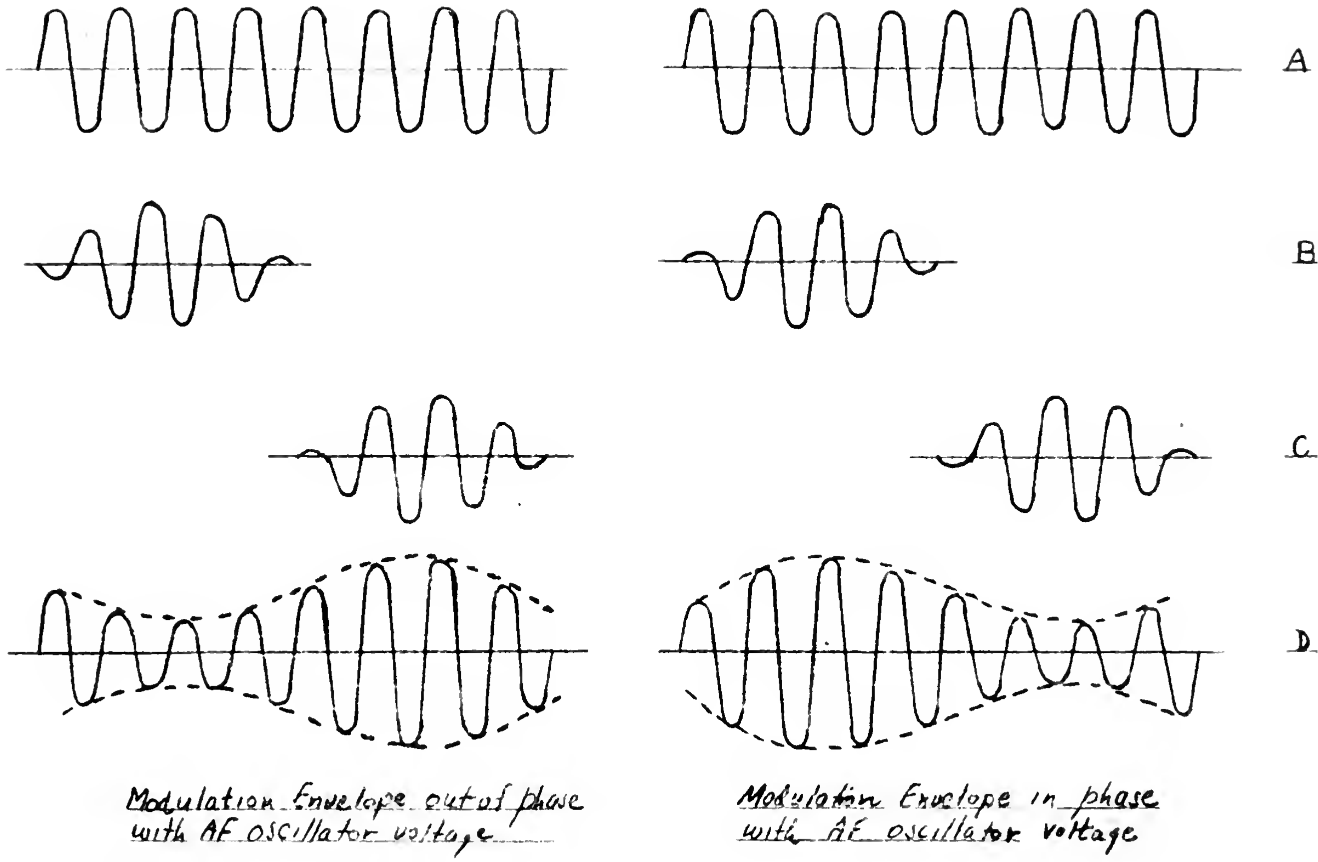
A loop signal input to balanced modulator (after 90° Shift)
B AF modulating voltage to first half of balanced modulator
C AF modulating voltage to second half of balanced modulator
D output from first half of balanced modulator
E output from second half of balanced modulator

FIGURE 5.



Rotating Loop System

FIGURE 6



A Sense Antenna Signal

B Output from first half of balanced modulator

C Output from Second half of balanced modulator

D Resultant Signal after adding both halves of balanced modulator output to sense antenna signal

FIGURE 7

loop is between zero degrees and 180 degrees and in the opposite direction for bearings between 180 degrees and 360 degrees, it is evident that the loop will always drive to a null. The usual loop system uses a two phase a.c. motor which requires that its two fields be excited by two voltages of the same frequency and of 90 degrees phase difference. If this difference is of one algebraic sign, the motor will rotate in one direction, while if the sign is reversed, the direction of rotation will also be reversed.

From the detector the audio signal is passed through a 90° phase shift network and amplified. The output of this amplifier is coupled to one winding of the loop motor. The direction of rotation of this motor is determined by the phase (+90 or -90) of the 115cps voltage applied to this winding with respect to that applied to the other winding derived from the 115 cycle source. This phase is, in turn, determined by the position of the loop. The 115cps reference voltage is coupled to the other winding of the loop motor. The 115cps voltage derived from the loop signal will cause the loop motor to rotate the loop to the null position where no signal is received.

loop is [illegible] zero [illegible] 180 degrees [illegible] direction [illegible] between [illegible] and 360 degrees, it is evident that the [illegible] a null. The [illegible] a two phase a.c. motor [illegible] two fields [illegible] by two voltages [illegible] 90 degrees phase difference. If the difference [illegible] sign, the motor will [illegible] one direction; [illegible] sign is reversed, the direction of rotation will also be reversed.

From the [illegible] signal is passed through [illegible] phase shift network [illegible]. The output of this small [illegible] to one [illegible]. The [illegible] motor is [illegible] (+ or -) [illegible] of the [illegible] voltage applied to this [illegible] with respect to that applied to the [illegible] winding derived from the [illegible] source. [illegible] phase [illegible], in turn, determines [illegible] of the loop. The 115 cycle reference voltage is coupled [illegible] of the loop motor. The 115 [illegible] derived from [illegible] will cause the loop motor to rotate the loop to the null [illegible] signal is received.

CHAPTER TWO

FIXED LOOP SYSTEMS

Worthy of mention among direction finder systems using loop antennas are those using fixed loops. Normally the system consists of two loops at right angles to each other. One loop (A) receives signals proportional to the sine of the azimuth angle (ϕ) of the arriving signal. The other loop (B) receives signals proportional to the cosine of the azimuth angle of the arriving signal.

In a system[3] using this type antenna the output of loop A (see figure 8) is coupled to a radio frequency switch (switching at frequency f_1). The output is a constant amplitude signal consisting of e_1 and e_2 (voltages from either side of the loop). These voltages (e_1 and e_2) are 180 degrees out of phase with each other since the switch is fed from either end of the loop A to ground. The output of loop B is coupled to a radio frequency switch (switching at frequency f_2). A sense antenna signal is shifted 90 degrees and combined with each of the outputs of the radio frequency switches. When voltages e_1 and e_2 are added to the sense antenna voltage, the result is a square wave modulated signal. Similarly e_3 and e_4 (voltages from switch B) give square wave modulated signals. When these two square wave signals are added they result in a complex envelope. This envelope is non-recurrent in shape due to the choice of frequencies f_1 and f_2 having non-integral relationship.

The resulting radio frequency signal passes through a conventional receiver. The detector output consists of the combination of two square

[illegible]

[illegible]

[illegible]

antennas are [illegible] loops. [illegible]

of two loops at right angles to each other. [illegible] receiver

signals are [illegible] of the

arriving signal. [illegible] receiver (?) [illegible]

the center of the [illegible] arriving signal.

[illegible]

figure [illegible]

f_1). [illegible] and

e_2 [illegible]

are [illegible] from the [illegible]

from [illegible] ground. The output of loop 1 is equal

to a [illegible] frequency f_1). [illegible]

signal is [illegible] of the

the [illegible] and [illegible] the

sense [illegible] the signal.

Similarly [illegible]

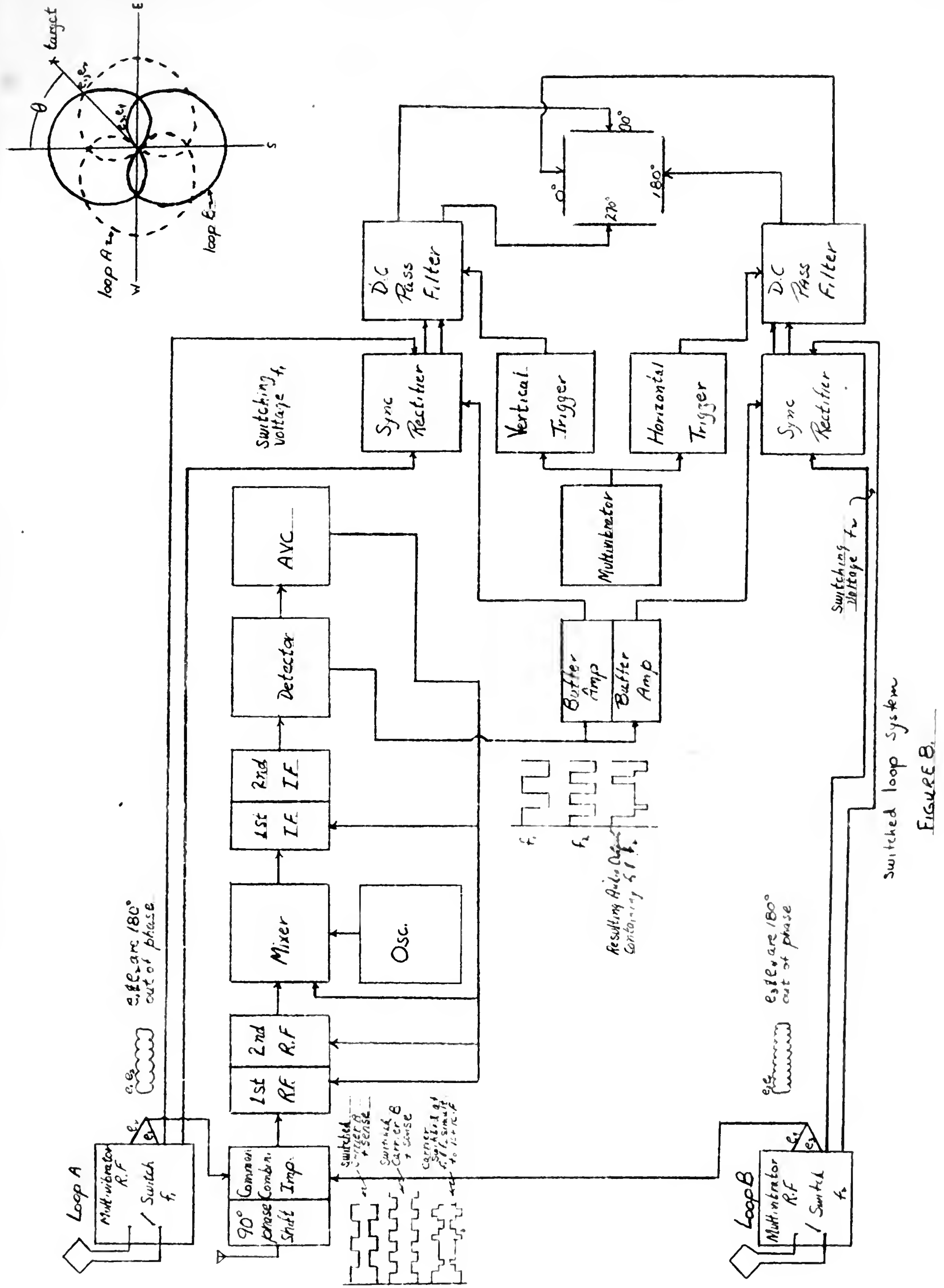
[illegible]

[illegible]

[illegible]

[illegible]

[illegible]



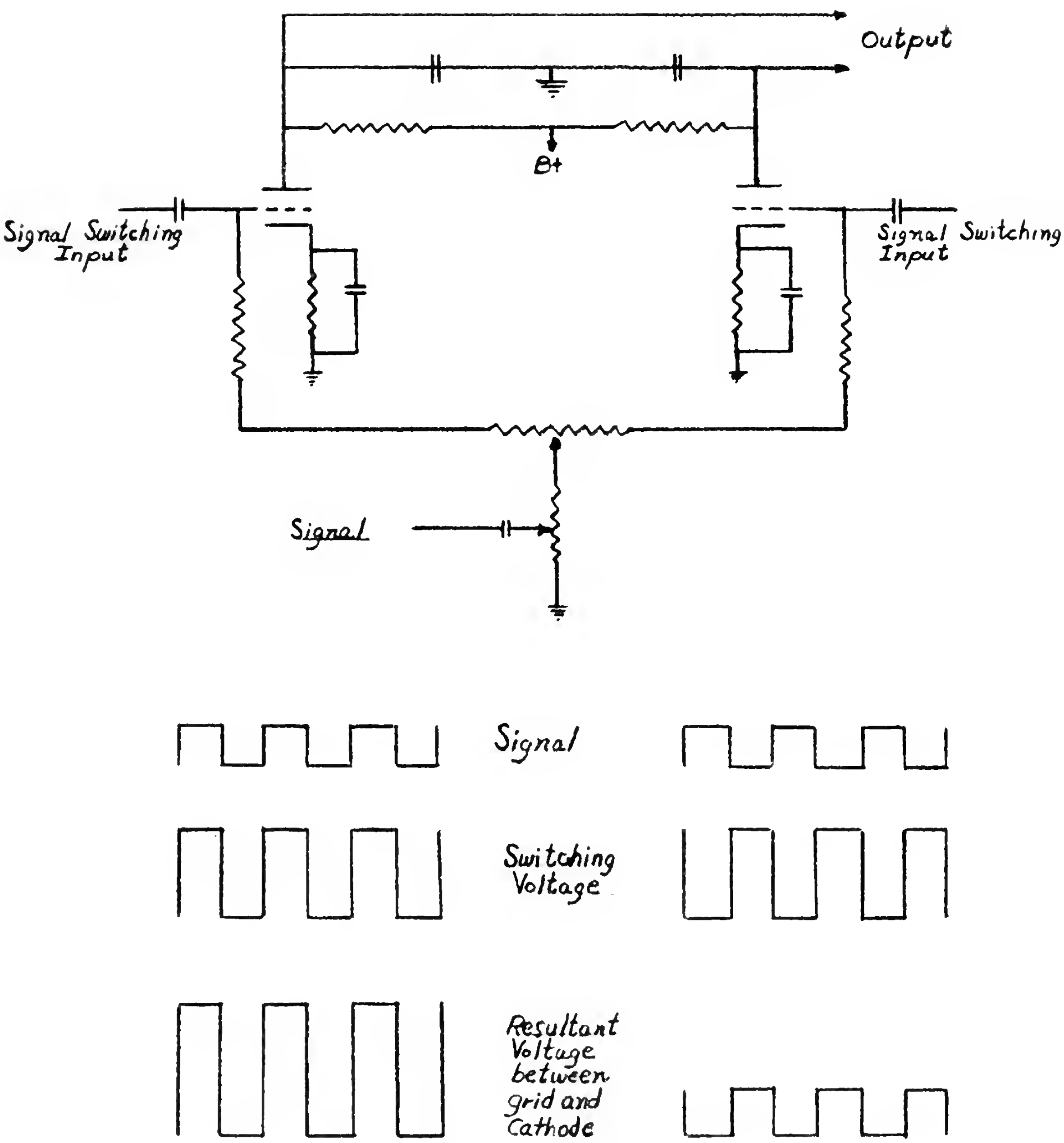
Switched loop system

FIGURE 8.

waves of frequencies f_1 and f_2 and is coupled to buffer amplifiers and thence to synchronous rectifiers. The synchronous rectifiers segregate the N-S and E-W intelligence and provide d c voltages which are proportional thereto. Fundamentally the circuit consists of two triodes operated as balanced modulators, as shown in figure 8a. Each rectifier is switched synchronously with its associated radio frequency input circuit. The detector output is coupled to the triode grids in parallel, while the square-wave switching voltage is applied in push-pull. Each tube is biased to have the tube operate Class A during the "on" period of the switching cycle and cut off during the "off" portion of the cycle. A difference voltage is produced at the plates of the rectifiers which is proportional in magnitude to the peak amplitude of the input square wave of like frequency. The polarity of this difference voltage is determined by the relative phase of signal and synchronous voltage applied to the grids of the synchronous rectifier. The output voltage is then connected to an appropriate pair of oscilloscope deflection plates. The oscilloscope electron beam is deflected out in an X and Y direction proportional to cos ϕ and sin ϕ and therefore indicates the direction of arrival of the signal.

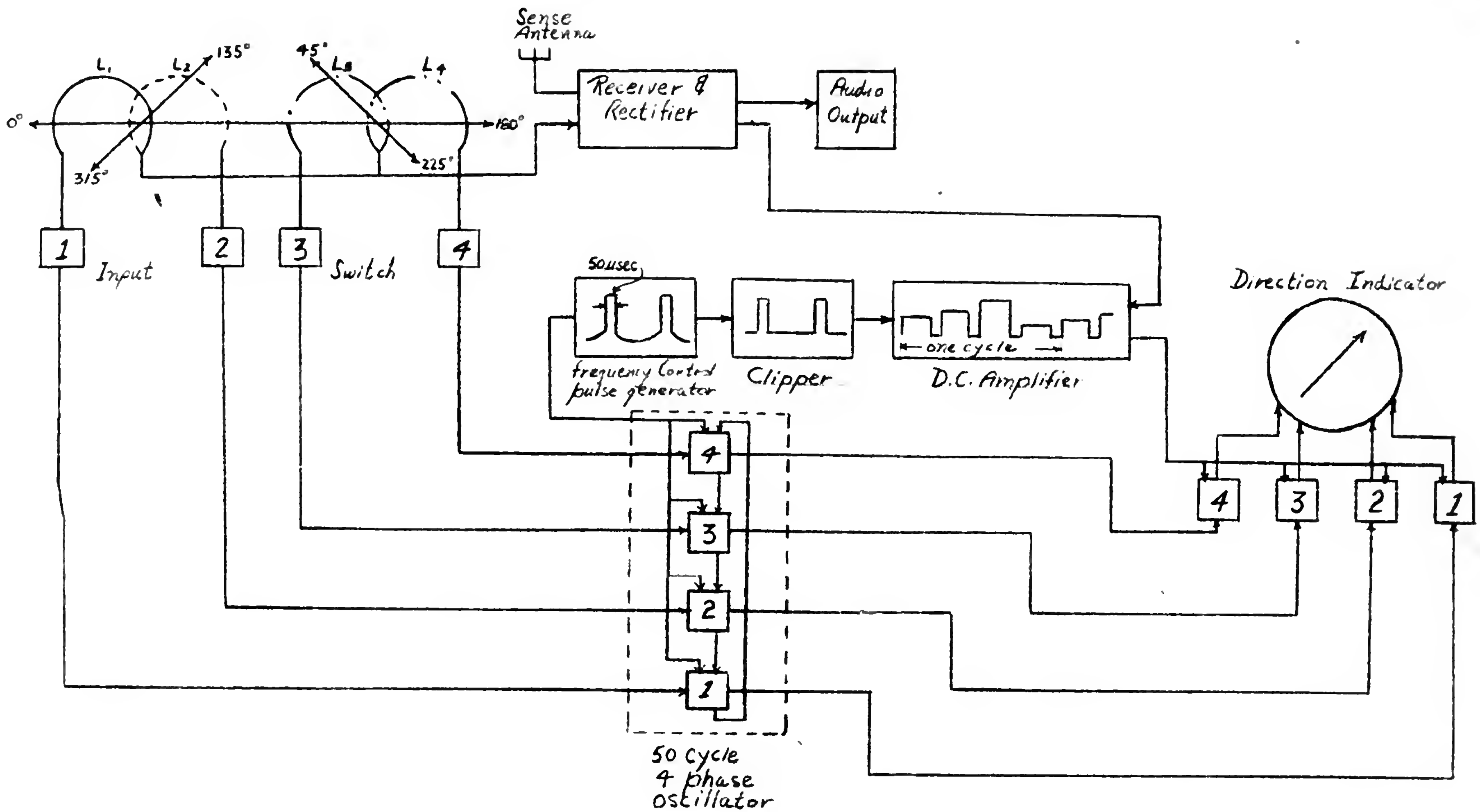
A variation of this system (see figure 9) makes use of four loops connected in two pairs.[4] Each pair is oriented 90 degrees from the other pair. When the signal voltages from each coil are combined with the sense antenna voltage, they result in four heart-shaped patterns of reception, each pattern 90 degrees removed from each other. The voltage induced in each loop depends on the azimuth angle of the received waves [illegible] is applied [illegible] and [illegible] frequency [illegible] the [illegible] quency [illegible] voltage [illegible] momentarily the circuit consists of two triode operated [illegible] as shown in Figure 26. Such [illegible] is [illegible] frequency in it circuit. [illegible] triode grids in parallel, while [illegible] voltage is applied in push-pull. [illegible] tube [illegible] during the first period of the [illegible] during the [illegible] portion of the cycle. A difference [illegible] of the rectifiers which is [illegible] the [illegible] of the input [illegible] wave of [illegible] of [illegible] there is determined [illegible] voltage applied to the [illegible] rectifier. The output voltage is then connected [illegible] oscilloscope deflection plates. The oscilloscope [illegible] portions [illegible] arrival [illegible].

[illegible] connect [illegible] plate [illegible] pairs [illegible] from [illegible] same [illegible] result [illegible] shaped [illegible] record [illegible] convex [illegible] [illegible]



Synchronous Rectifier

FIGURE 8a



ultiplexed loop system

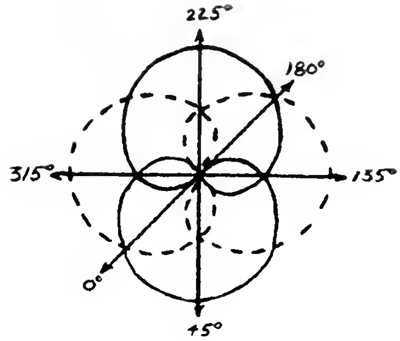
FIGURE 9.

signal (see figure 10). Each of the loop voltages is sequentially sampled for a fraction of a second several times a second, amplified by a receiver and a D.C. amplifier. This results in an output waveform having the same fundamental frequency as the sampling frequency and each cycle divided into quarters. This is accomplished by making the sampling time equal to one quarter the period of the sampling frequency. The amplitude of each quarter cycle is proportional to the voltage picked up in the corresponding antenna loop coil.

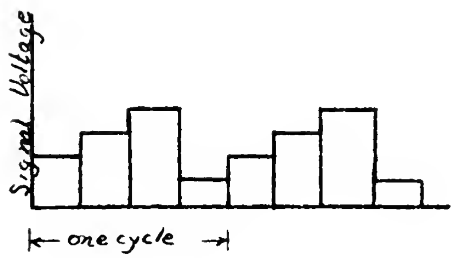
The switching systems are unique and interesting. The master control for input and output switching consists of four blocking oscillators which use similar circuit values and each is inductively coupled to the preceding oscillator. Each stage is activated by the termination of the preceding stage conduction. Absolute control of the period of conduction is accomplished by making use of a separate pulse generator which limits the conduction time of each stage to about fifty percent of its normal period.

Connected in series with each loop coil is a germanium crystal which acts as a varistor and forms an input switch. Each crystal is individually activated by the cathode current of a corresponding blocking oscillator. In this manner one circuit is completed while the other circuits are virtually open due to the back voltage across the crystals.

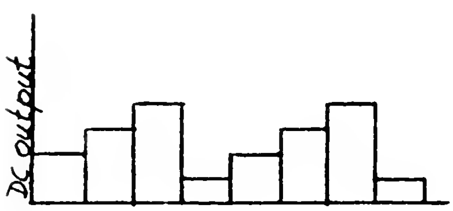
The output switching system consists of four thyratrons having identical load resistors and utilizing a common cathode resistor through an inductance. The voltage across this inductance caused by current flow through any of the thyratrons is sufficient to bias the other three



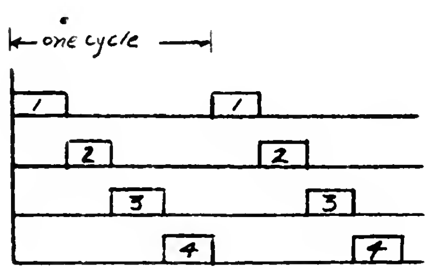
Cardioid Patterns



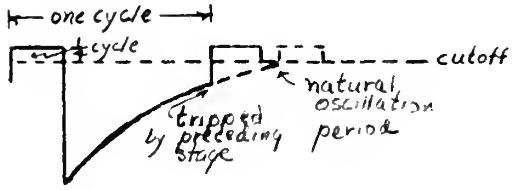
Signal Voltage Applied to Receiver



Output of D.C. Amplifier



Oscillator Cathode Voltages



Oscillator Waveforms

Figure 10

thyratrons below cutoff. Output switching consists of coupling a momentary negative pulse to the grid of the direct current voltage amplifier by means of a winding on the frequency control pulse generator transformer. This causes the voltage amplifier to cutoff and removes plate voltage from the conducting thyratron and deionizing it. Simultaneously, the grid of the following thyratron is driven more positive, permitting ionization by virtue of the reduced grid bias resulting from the corresponding four phase oscillator triode's conducting.

CHAPTER THREE

VERTICAL ANTENNA SYSTEMS

A loop antenna is susceptible to polarization errors (as discussed in Chapter Five) and from attempts to reduce this fault, the use of vertical antennas evolved. The reasoning that voltages induced in the horizontal members of the loop was the cause of polarization error led engineers to try to eliminate the horizontal members. From studies in this direction evolved the well-known ADCOCK antenna system for use in direction finders. Today most ground station direction finders use several vertical antennas from which they derive the information.

Basically a single element could be used if it were moved around some closed path. In this manner the distance from the transmitter to the element will vary with time and the voltage induced in the element will be modulated in phase. The type and extent of the modulation depends on the size and shape of the path the element follows. The frequency of the modulation envelope will be the same as the frequency with which the element travels the path. In particular, the phase modulation envelope will be related in some definite manner in time to the direction of arrival of the received signal and thus its direction may be obtained from the time/phase relationship of the phase modulation envelope.

The time reference can be fixed by the movement of the element itself. By converting the movement to a voltage wave, the bearing can be derived by comparing the constant phase of the motion-derived voltage and bearing dependent phase of the signal phase modulation envelope.

If the motion of the element is confined to a circle, then both the motion-derived voltage and the signal phase modulation will be sinusoidal. By linearly demodulating the phase modulated signal, there results a sinusoidal voltage having the same frequency and phase as the original phase modulation envelope. The demodulator output voltage and the reference voltage are compared to give the desired bearing information. The system is inherently accurate because, owing to the linearity of the process of modulation and demodulation, no spacing or repetitive error can be produced.

This scheme presents one insurmountable obstacle in that it is practically impossible to rotate the element antenna in a circle. A physically realizable circle is so small compared to a wavelength that the amount of modulation would be too small. Rather than rotating one element in a circle, a number of similar elements equally spaced around a circle may be used; the voltage induced in each element being sequentially sampled. In this manner the same effect as rotating the single element is derived. Instead of a continuous modulation however, this system generates a series of abrupt changes of phase. Simple phase-demodulators or discriminators are not linear in action over a very large rate of phase change. In particular, an instantaneous change of phase represents frequency modulation whose envelope is an impulse function clearly exceeding the linear range of a practical discriminator. Repetitive error is hence encountered which is due to the distortion of the phase of the wanted component in the audio frequency output by secondary demodulation products of the same fundamental frequency, which exist because of the non-linear characteristic of the discriminator.

In order to obtain as much linearity as possible in the process of demodulation and hence restrict the size of the repetitive error, it is customary to compress or reduce the phase excursion of the signal before applying it to the discriminator. The compression of the phase is achieved by delaying part of the signal for a time equal to, or to a multiple of, the period of activity of one element and then deriving a secondary signal that has a phase modulation whose extent at any instant is equal to the instantaneous difference between the phase modulation of the delayed and non-delayed parts of the signal. The phase excursion on the secondary signal will be smaller than that on the original because a process of differencing has, in effect, been applied to the original phase modulation.

The delay method may be eliminated if two elements are assumed to be rotated simultaneously in a circular path. Comparing the direct output voltage of these two elements yields the same resultant differential phase modulation. This method has the advantage that any random fluctuations of signal carrier phase is received simultaneously by both elements and vanishes when the phase measurement is made. If the signal from one element of a pair is displaced in frequency, a secondary signal of constant mean frequency is obtained when the two signals are combined. Demodulating this signal and comparing it to the phase of a reference voltage gives a direct and unambiguous measure of bearing.

A system (2-20 mc) using single-positional commutation[5] operates as follows (see figure 11.). Twelve vertical aerials are equally spaced around the circumference of a circle approximately 150 feet (45 meters) in diameter. The rectangular positive pulses, of 'on/off' ratio 1:11, In [illegible] with the [illegible] of

[illegible] with [illegible]

[illegible] applying it [illegible] by delaying [illegible] the signal for [illegible], the period of [illegible] and then deriving a secondary signal [illegible] in [illegible] equal to the [illegible] between the [illegible] of the delayed and [illegible] of the signal. The phase [illegible] in the [illegible] than that on the original because a [illegible] has, [illegible], been applied to the original phase modulation.

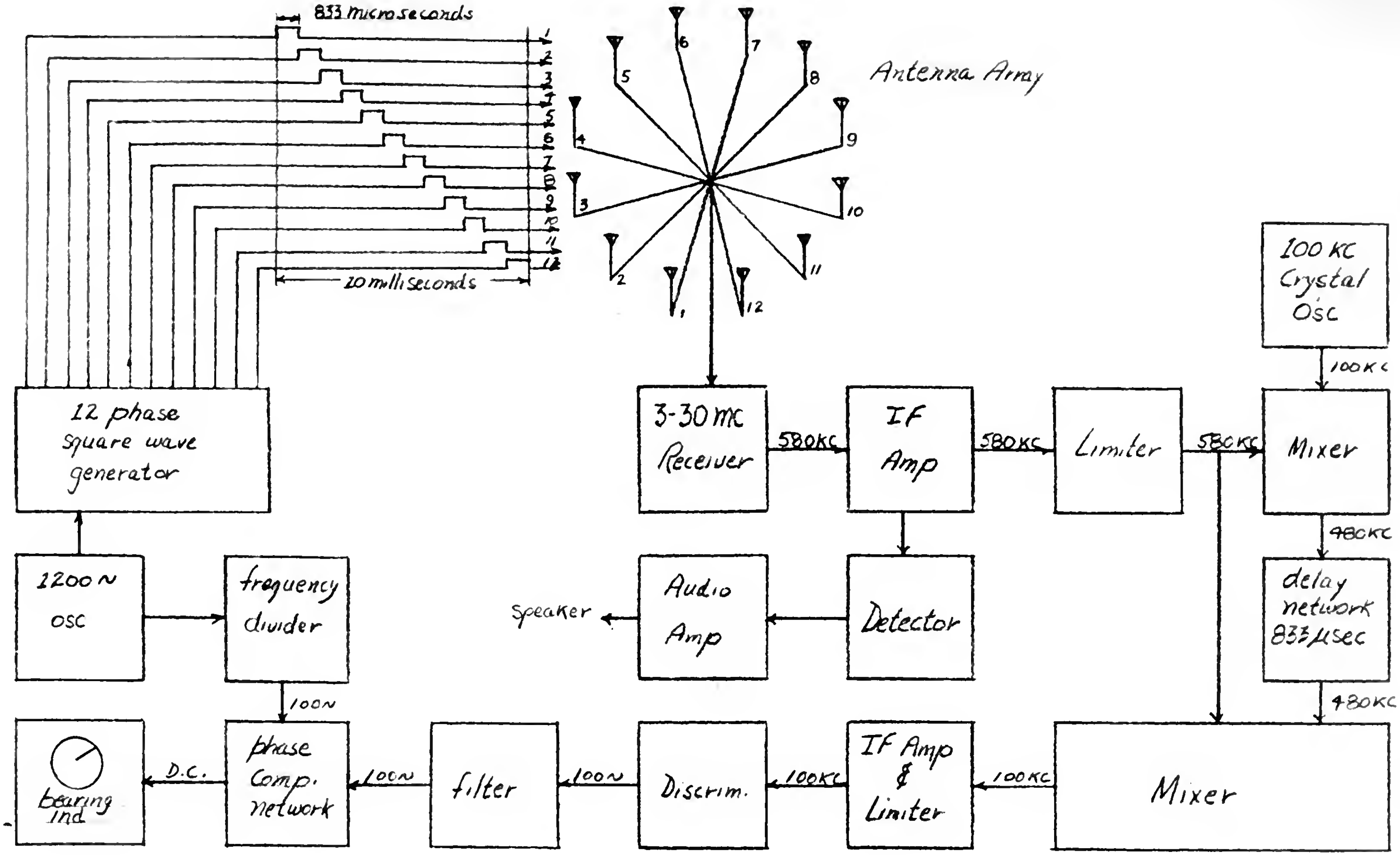
The third method [illegible] of two elements [illegible] to be [illegible]. Comparing the direct output voltage of these two elements yields the same resultant differential phase modulation. This method has the advantage that any [illegible] the time of [illegible] be resolved [illegible] by both elements and [illegible]. If the signal from one [illegible] the phase, [illegible] signal [illegible] [illegible] voltage [illegible].

[illegible]

Follow [illegible]

[illegible]

[illegible]



Single Positional Commutation System

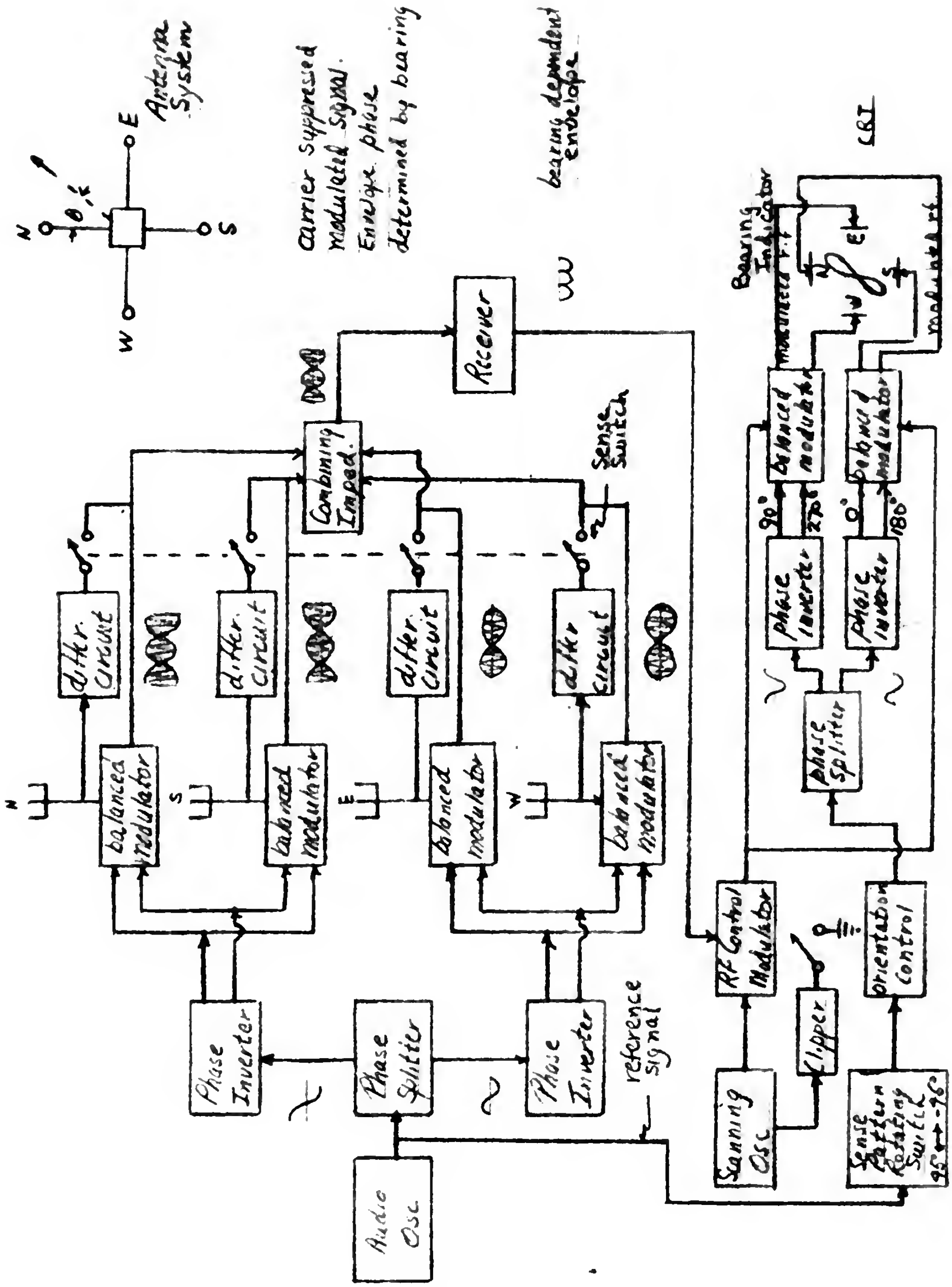
FIGURE 11

used to sample the antenna output are obtained in the correct time sequence from a 12 phase phantastron generator, which operates at an overall frequency of 100 cycles. The commutated radio frequency signal derived from the antennas is fed to a conventional superheterodyne receiver and the IF (580 kc) frequency is limited and mixed with a 100 kc crystal controlled oscillator output. The difference frequency of 480 kc is passed through a 833 microsecond delay network. This delayed signal is then mixed with the original undelayed 580 kc signal and a 100 kc difference frequency is obtained, which is of constant carrier frequency. This is further limited and then subjected to the action of a sinusoidal discriminator from which an audio frequency wave of 100 cycles is obtained. The 100 cycle output of the discriminator and the 100 cycle reference from the 1200 cycle oscillator are compared in a phase comparing network and the DC output actuates a cathode ray presentation.

The complexity of the above system may be avoided in a system[6] which uses an antenna system consisting of four omnidirectional antennas (see figure 12) uniformly spaced on the circumference of a circle. The field of the received wave at the center of the antenna system is taken as a phase reference. This system differs from the usual system in that the collector elements are not combined directly in pairs to produce the crossed 'figure-of-eight pattern' of reception. In this system each collector element is independently modulated in an individual balanced modulator and signals from alternate collectors are modulated in quadrature. Four equal amplitude modulated carrier-suppressed signals are produced. Each carrier-suppressed signal has a fixed envelope phase but the high frequency phase is a function of the horizontal direction of

used to [illegible] the [illegible] output [illegible] [illegible] [illegible] the
a [illegible] [illegible] [illegible] generator, [illegible] [illegible]
overall frequency of 100 cycles. [illegible] [illegible] frequency [illegible]
entire [illegible] [illegible] [illegible] frequency [illegible]
center on the [illegible] (500 kc) frequency [illegible] and mixed with the
crystal oscillator [illegible] output. [illegible] frequency of 100 [illegible]
is passed through a [illegible] frequency [illegible]. This output signal
is then mixed with the original output [illegible] and [illegible]
difference frequency is obtained, which [illegible] a [illegible] frequency.
This is further limited and then [illegible] of a [illegible]
discriminator from which an output [illegible] of 100 cycles is
obtained. The 100 cycle output of the discriminator and the 100 cycle
reference from the [illegible] cycle oscillator are [illegible] in a phase comparing
network and the DC output actuates [illegible] to correct them.

The complexity of the above system may be avoided in a system which
uses an antenna system consisting of [illegible] [illegible] antennas (see
Figure [illegible]) uniformly spaced on the [illegible] of a circle. The [illegible]
of the [illegible] [illegible] system is taken as a
phase reference. This system differs from the usual system in that the
collector [illegible] in place to [illegible]
crossed [illegible] [illegible]. In this system the
collector [illegible] is independently rotating [illegible]
not [illegible] and [illegible] [illegible]
[illegible]. [illegible] this are
[illegible] [illegible] but
[illegible]



combined antenna system
Figure 12.

arrival of the signal. These four signals are additively combined in a common impedence and a resultant signal is obtained that sinusoidally varies as the angle of arrival of the wave, the carrier frequency, and the modulating frequency.

In this system use is made of a novel phase meter method of presentation and measurement by means of a cathode ray tube. A linearly polarized field is obtained from two oppositely directed circularly polarized fields. The circularly polarized fields result from the combination of a scanning oscillator and the modulating frequency in two balanced modulators. The scanning oscillator frequency is applied in phase to the modulators while the modulation frequency is applied in quadrature to the same modulators. The upper sideband from one modulator is in phase quadrature with the upper sideband from the other. One modulator output is applied to the vertical deflection plates of the cathode ray tube while the other modulator output is applied to the horizontal plates. Since the sidebands are in phase quadrature and they are applied to space quadrature plates, they produce a circularly polarized field. Similarly the lower sidebands produce a second and oppositely directed circularly polarized field. These circularly polarized fields differ in frequency by twice the modulating frequency and the effective phase difference between them changes at the rate of twice the modulating frequency. The plane of rotation of the linearly polarized field will rotate if the relative phase of the circularly polarized fields is changed. This rotation is equal to half the difference in phase. Hence the cathode ray beam is acted upon by a linearly polarized deflecting field which rotates with the same frequency as the modulating frequency.

CHAPTER FOUR

OMNI DIRECTIONAL RANGE

A more elegant form of direction finder has evolved in later years and is called 'omnirange.' The omnidirectional range has elements in common with all other types of radio ranges and direction finding systems, and represents a refinement in practice rather than a fundamental departure in principle. It resulted from the need to replace the presently existing systems of radio beacons which afforded only a few (usually four) selected approach paths to a desired location.

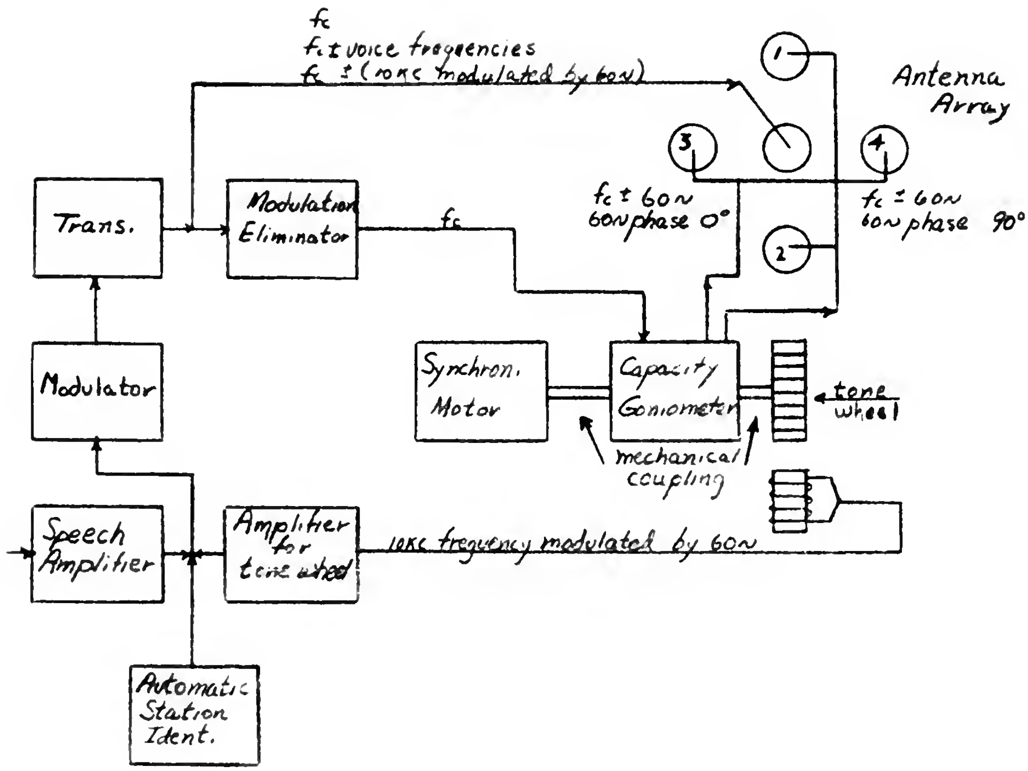
In the basic omnirange system[7] an antenna having a heart-shaped pattern is rotated so that its field strength at any point in space varies as a sine wave. This sine wave frequency is the same as the rotation speed of the antenna and the phase of the sine wave is proportional to the azimuth angle around the omnirange station. True azimuth angle may be obtained by comparing a reference signal of constant phase synchronized with true north with the received signal. One degree of phase will then equal one degree of azimuth.

Greater accuracy can be obtained at microwave frequencies by using greater phase shift per degree of azimuth. By superimposing the pattern from an antenna having several lobes or scallops (for example, 11 lobes) on the original single heart-shaped pattern, it is possible to have eleven cycles of sine wave for one complete rotation of the antenna and one degree in phase equals one-eleventh of a degree of azimuth. There is no ambiguity present because the average value of the eleven cycles varies as the sine wave produced by the heart-shaped pattern. This sine

wave may then be used as a coarse measure and the sine wave from the eleven cycles can be used as a fine measure.

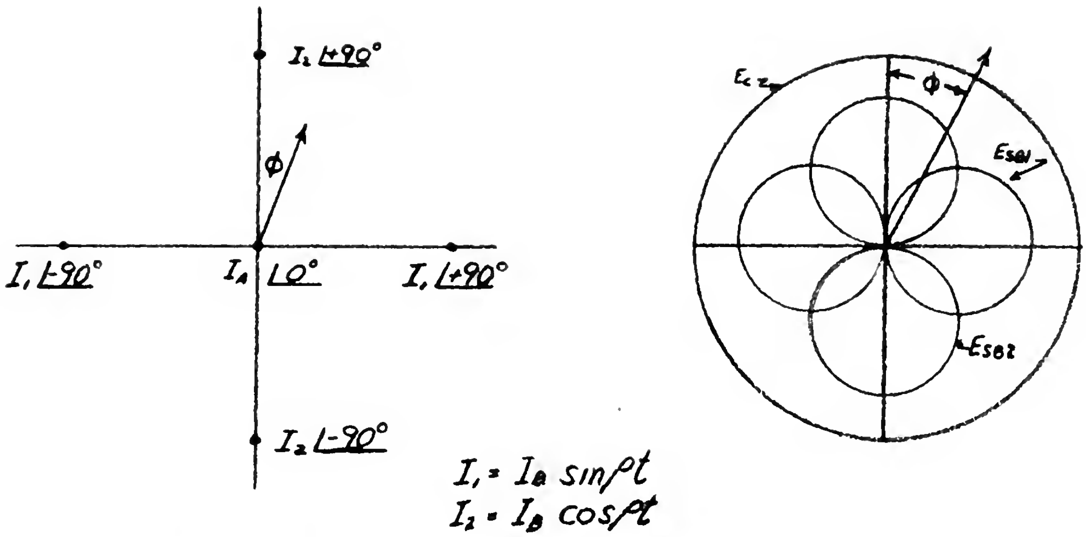
The receiver in this system receives four signals-- 'a coarse' and 'a fine' variable phase signal which represents azimuth and 'a coarse' and 'a fine' constant phase reference signal which represents north. Two phase detectors compare the 'coarse' and the 'fine' signals-- the reference signal being shifted before applying it to the detectors. This phase shift is caused by the output of the phase detectors and continues to be present until the reference and variable signal have the same phase.

The previously described system entails many complexities in the design of a rotating antenna and the use of the eleven cycle pattern superimposed on the original cardioid. A system[8] which by-passes these difficulties and performs the same functions but with less accuracy uses a fixed antenna system of five radiating elements located approximately at the corners of a square and at the center of the square (see figure 13). Opposite pairs of antennas are operated 180 degrees out of phase and the electrical spacing between the elements is small compared to the wavelength. The pair of antennas with currents I_1 (see Figure 13a) produces the figure-of-eight pattern E_{SB1}. Similarly, the pair of antennas with currents I_2 produces the pattern E_{SB2}. The centre antenna with current I_A radiates the E_c pattern. The three patterns combine in space to produce an amplitude-- modulated wave whose modulation frequency is $\rho/2\pi$. The most significant characteristic about this amplitude-- modulated wave is the phase angle of the modulating frequency, which varies as the azimuth angle, ϕ, for small values of spacing.



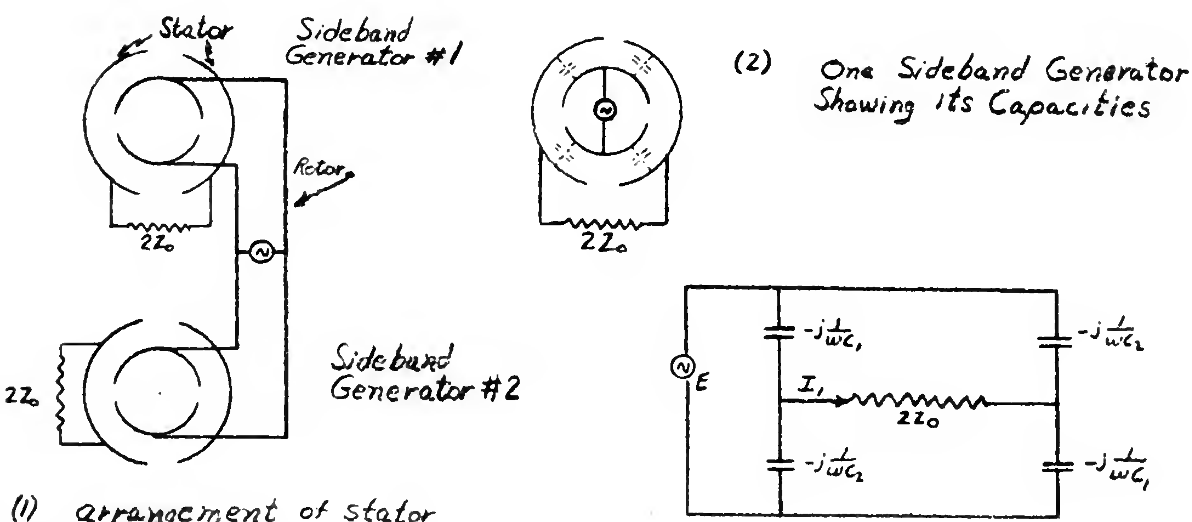
Omnirange Transmitter

FIGURE 13



horizontal field pattern - omnirange transmitter

FIGURE 13a



(1) arrangement of stator and rotor plates

(3) schematic of (2)

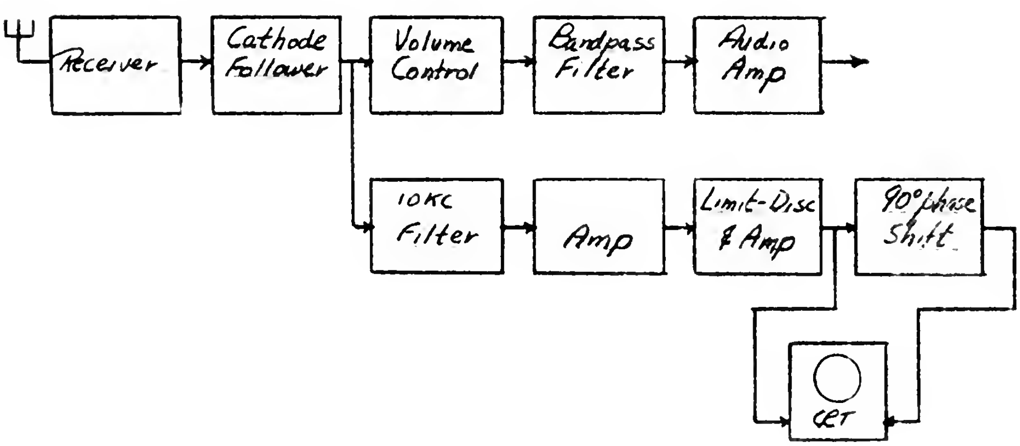
capacitor goniometer

FIGURE 13b

In this system the antenna array is not rotated but the array pattern is rotated by means of a capacitor which is driven by a synchronous motor at 3600rpm. This capacitor (called a goniometer) consists of two mechanical sideband generators on a common drive shaft, rotating at 3600 rpm. One sideband generator is oriented 90 degrees with respect to the other so that the electrical outputs of the two generators are in phase quadrature at the modulation frequency, as shown in Figure 13b. The currents flowing in the loads 2Zo of Figure 13b are of two frequencies, one higher and the other lower than the carrier frequency by the goniometer rotational frequency. Also, the number-1 and number-2 outputs consists only of sidebands that are 90 degrees out of phase at the modulation frequency.

In this manner each direction in space will have certain phase relationship of the rotational frequency since the pattern effectively rotates. Each degree of phase equals one degree of azimuth and can be compared to a reference signal provided by sixty cycle modulation applied to a 10 kilocycle subcarrier which, in turn, modulates the carrier radiated from the antennas. A small shaft driven by the synchronous motor which rotates the capacitor provides the reference modulation. Thus a constant phase relationship is provided between the two signals.

The omnirange receiver (see figure 14) consists of a typical VHF superheterodyne up to and including the second detector. Following the second detector is a cathode follower and a filter to separate the 10 kilocycle subcarrier and a third detector to detect the reference phase voltage from the modulated subcarrier. The reference voltage is amplified and applied to one set of deflecting plates of a cathode ray oscilloscope.



Omnirange Receiver

FIGURE 14

This same audio frequency is shifted 90 degrees and this shifted frequency is applied to the second set of deflecting plates. In this manner a Lissajous figure is formed consisting of a circle made by motion of the cathode spot. Effectively the cathode spot rotates in a circle at a speed which is directly a function of the audio frequency. This spot then occupies a position on the screen corresponding to the phase of the modulating frequency at the transmitter and the position of the receiver with respect to the transmitting station.

In this system, in addition to the provisions previously mentioned, a method is provided for momentarily stopping all transmissions when the maximum of the cardiod reaches a true north position. When ever this momentary stopping of the transmission occurs, the spot will no longer be affected by the deflecting plates and it will tend to travel to the outer edge of the screen. It returns to its orbit as soon as the radiation is again present. The result is a circle with a vee notch on its periphery. The position of the notch is the bearing of the receiver with respect to the transmitting station.

CHAPTER FIVE

LIMITATIONS OF SYSTEMS

Although direction finding affords many useful applications it is unfortunately inherently subject to error which reduces its usefulness, unless these errors are recognized and taken into account. Basically any type of radio compass is simple to use; a great deal of care is required, however, if reasonable accuracy is to be obtained. Under the best conditions of navigation and good received signals, the errors are limited to $\pm 2^{\circ}$. Usually, however, they range from $\pm 3^{\circ}$ to $\pm 5^{\circ}$. The accuracy depends not only on skilled operation and steady flight but also on the accuracy of calibration of the antenna system. This calibration must be done carefully for each aircraft (or vessel) and for each position of the antenna (if rotating) because the metal structure of the aircraft (or vessel) varies the amount of energy received by the antenna from certain directions.

The most outstanding disadvantage of the loop antenna is its ability to follow swinging bearings caused by ray interference due either to waves reflected from the ionosphere or from mountainous country over which the aircraft is traveling. This is usually called 'night effect'. Normally the loop receives horizontally propagated rays. However, the reflection from the ionosphere and mountains cause the propagation path to become diagonal causing the arriving wave to have vertical as well as horizontal propagation components. The horizontally propagated component results in a magnetic field in the horizontal plane

and the loop pickup is zero when the magnetic field is parallel to the plane of the loop.

The downward directed wave may be either of two cases. The plane of polarization may either lie along the direction of propagation or rotated 90 degrees to the direction of propagation. The former is called a 'normally polarized' wave while the latter is called an 'abnormally polarized' wave. The 'normally polarized' wave does not affect the operation as it results in a magnetic field parallel to the loop and hence the same null position as the horizontally propagated component. In each case of normal polarization the magnetic field is perpendicular to the direction of propagation. The 'abnormally polarized' wave, on the other hand, being rotated 90 degrees, results in a magnetic field vector parallel to the direction of propagation and hence gives an apparent bearing 90 degrees displaced in azimuth from that of the preceding cases. It is this component which accounts for the errors in medium wave direction finding at night and for the major errors at all times in short wave direction finders.

In the omnirange system aircraft propellers cause the received signals to modulate. As a result of this modulation the direction indication will oscillate depending on the amplitude and rate of the propeller modulation. A frequency of 30 cps for the variable and reference phase signals would be most desirable since the cruising propeller rpm of all known aircraft produces a propeller modulation frequency higher than 30 cps.

Regardless of the type system, reasonably good site location for the transmitter is required. Surfaces formed by objects, such as trees,

buildings, wires, hills, and the like, reradiate or attenuate energy from the antenna system.

CHAPTER SIX

FUTURE DIRECTION FINDER SYSTEMS

Essentially omnirange is the direction finder of the near future. Present trends and efforts are all directed toward a future system involving the integration of omnirange, distance measuring equipment, and instrument landing systems. Each will be separate and distinct systems working in conjunction with the others. Much greater accuracy and speed of presentation will be obtained by the use of high speed loop antennas (when used), motor driven tuning controls, crystal oscillators, use of turret tuners, and any other mechanism (mechanical or electronic) that will make the system as near fully automatic as possible.

At present a system[9] is being evaluated which includes a 35 mm film strip projector, very much like a slide projector, installed behind a 10 inch translucent screen. The film cartridge contains 100 feet of film which furnishes as many as 700 navigational charts, each centered at an OBD ground station (OBD is the abbreviation for a combined omnirange and distance measuring equipment.). Important areas may be represented on several different charts which are drawn to different scales. When the pilot selects an appropriate chart and adjusts the illumination level, the electronic equipment starts to operate. Coded holes punched in the film energize equipment to tune the receiver to the correct OBD station and match the scale of the computing mechanism

to the scale of the chart. A miniature airplane is positioned by two servomechanisms on the projected image of the chart. A third servomechanism orients the miniature plane and an attached arm in accordance with the magnetic heading of the actual plane. Position should be indicated correctly to 0.4 mile in distance and approximately 0.5 degree in azimuth. The maximum range is 115 miles and the pilot changes the charts at 20 to 30 minute intervals on the average. Thus with a compact, simple, and up to date presentation of his situation constantly in view, the pilot may choose to follow the course by manual control, or may apply appropriate instructions and corrections to the autopilot. This is the system of the near future and merely the promise of what is expected to follow.

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